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Testing of Packaging Materials for Improved PV Module Reliability

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TESTING OF PACKAGING MATERIALS FOR IMPROVED PV MODULE RELIABILITY

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ABSTRACT

A number of candidate alternative encapsulant and soft backsheet materials have been evaluated in terms of their suitability for photovoltaic (PV) module packaging applications. Relevant properties, including interfacial adhesion and moisture transport, have been measured as a function of damp-heat (85°C / 85% relative humidity) exposure. Based on these tests, promising new encapsulants with improved properties have been identified. Backsheets prepared by industry and at NREL have been found to provide varying levels of moisture ingress protection. To achieve significantly improved products, further development of these candidates is ongoing. The relative effectiveness of various packaging strategies to protect PV devices has also been investigated.

INTRODUCTION

To survive in harsh operating environments, PV modules generally rely on packaging materials to provide requisite durability. These include glass/glass and glass/breathable backsheet constructions laminated with various encapsulant and/or edge-seal materials. Thin-film PV manufacturers are interested in replacing glass backsheets (and possibly frontsheets) with soft cover layers. Such constructions can eliminate glass breakage due to edge pinching and provide a more durable mechanical package. In addition, lighter weight can lead to lower cost. Alternative encapsulants that provide better moisture-barrier properties and improved adhesion with weathering are also being contemplated. For some configurations in which a thin-film device is directly deposited onto a clear superstrate material, solar transparency of the encapsulant is unnecessary. This expands the number of candidates that can be considered, allowing the use of less expensive materials and lamination processes. To achieve these benefits, the reliability of the resulting PV module must be demonstrated. In particular, the damaging effects of moisture ingress must be averted. Water can weaken interfacial adhesive bonds, resulting in delamination and increased ingress paths, consequent loss of passivation, electrochemical corrosion, and ultimately, device failure.

The ability of combined packaging elements to protect thin-film aluminum coatings deposited onto glass substrates was assessed as a function of damp-heat exposure. Glass/glass laminate constructions were often found to trap harmful compounds that catalyzed moisture-driven corrosion of the aluminum. Constructions with breathable backsheets allow higher rates of moisture ingress, but also allow egress of corrosive substances.

EXPERIMENTAL

A number of new encapsulants and backsheets have been evaluated as improved packaging materials. The primary properties of interest were adhesion (using an Instron 5500R mechanical testing unit) as a function of damp-heat exposure, and moisture transport (measured with a Mocon Permatran-W® 3/31 instrument). Peel strength measurements (both 90° and 180°) have been made to allow screening of alternate encapsulant formulations and to test the durability of interfacial adhesion. Lap shear measurements were also made to allow more rigorous intercomparisons between different encapsulants, subjected to damp-heat exposure. By measuring the time-dependent permeability of backsheets and encapsulants the diffusivity and solubility of these materials can be derived and used to compute moisture-ingress time scales [1]. Finally, the ability of combinations of packaging components to protect PV devices from corrosion was assessed.

Encapsulants

NREL has investigated the adhesion properties of a number of candidate encapsulants. STR's standard fast-cure ethylene vinyl acetate (EVA) product (which contains a self-priming additive and is designated 15295P) was considered the control material. We have evaluated whether additional primers (used to prime glass substrates) or alternative substrate-cleaning procedures can improve the adhesion between glass and STR's EVA [2]. Other samples were also tested including silicones and primers from GE and Dow Corning, an experimental material from BRP Manufacturing (BRP-C), and an experimental fluorocarbon from Saint-Gobain (THV).

A number of silane adhesion promoters designed to improve adhesion of EVA to glass were screened by priming the glass substrates and preparing samples at NREL having the construction: TPE / EVA / Primed glass, where TPE is a commercial Tedlar-PET-EVA backsheet material (PET is polyethylene terephthalate) and EVA is STR's

15295P product. The 90° peel strength was measured between EVA and glass as a function of damp-heat exposure. Some samples demonstrated an improvement in adhesion compared to the STR control laminated to an unprimed glass substrate; some samples were so adherent that they did not initiate peel, even after 775 h exposure to damp-heat [2]. The most promising primers are being compounded into EVA for further testing.

NREL-prepared alternate encapsulant formulations were also tested [2]. These included EVA, and an ethylene copolymer of methacrylate with glycidyl functional groups having various silane coupling agents incorporated into the base resin. Some materials were found to be similar or inferior in performance to STR's 15295P EVA. However, one material was quite promising and experienced no peel initiation after 743 h of damp-heat exposure.

The lap shear strength of several encapsulants was measured as a function of damp-heat exposure (see Fig. 1). Significant loss in adhesion occurred for the EVA control material (EVA 85/85); a ~50% decrease in lap shear strength was found after 1000 h of exposure. Even at ambient temperature and humidity conditions (EVA Ambient), a noticeable loss (~20%) in lap shear strength results after 1000 h. The detrimental effect of moisture is evident by comparison with samples exposed to a room-temperature dry-air purge (EVA Dry 23°C), which shows no loss in adhesion. An experimental material from BRP Manufacturing demonstrated outstanding retention (even a slight increase) of lap shear strength with exposure (BRP-C 85/85). The THV material (THV 85/85) exhibited a precipitous drop in lap shear strength in a fairly short timeframe.

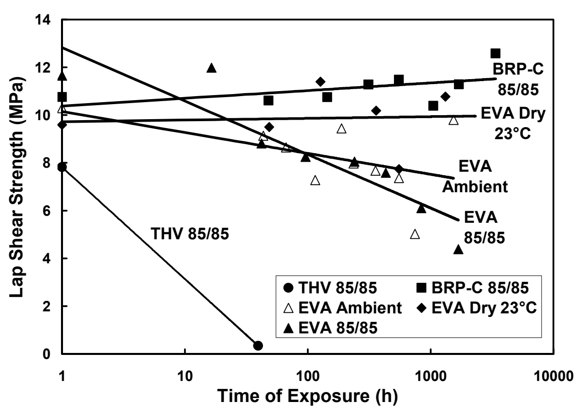

Fig. 1. Lap shear strength as a function of accelerated exposure.

The effect of two glass-cleaning procedures on the adhesion of EVA to glass was compared. One procedure used various acid treatments; the other used a commercial product (Billco #013-701) commonly used by the PV industry during their manufacturing process. The acid treatment resulted in a water-droplet contact angle of ~5°, whereas the Billco cleaning resulted in a contact angle of ~52°. Although the contact-angle measurements suggest significant differences in the cleaned glass surface energy, 90° peel strength measurements made as a function of damp-heat exposure were indistinguishable between the two cleaning methods (see Fig. 2). The sample construction was: TPE / EVA / Cleaned Glass.

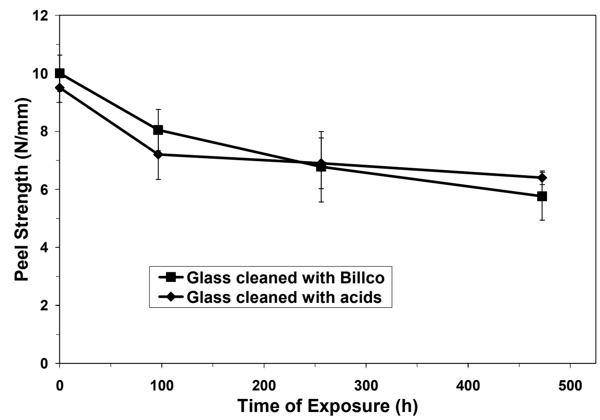

Fig. 2. 90° peel strength at EVA/glass interface as a function of accelerated exposure.

Backsheets

Polymer films coated with dense inorganic layers can provide improved moisture-barrier properties. We have previously investigated sputter-deposited inorganic coatings on PET as candidate backsheets for PV modules [3]. A number of other backsheet constructions have been characterized recently. These include an NREL plasma-enhanced chemical vapor deposition (PECVD)-coated PET, three commercial products from Isovolta, an experimental laminate from DuPont Teijin Films, ten PECVD-coated PET samples from AKT, two multilayer-coated PET samples from PNNL, and an uncoated/unlaminated liquid crystal polymer (LCP).

The various samples are at different stages of evaluation; preliminary adhesion and moisture transport results are summarized in Table 1. A series of hierarchical tests are typically performed. For polymer films with inorganic coatings, the quickest screening test is a Scotch tape peel test in which the tape is applied to the coating and peeled off. If none of the coating is removed, then it passes this test. Samples passing the tape peel test are then subjected to laminated peel strength and water vapor permeability characterization. Water vapor permeability was measured as a function of temperature (see Fig. 3). LCPs have very low permeability values, typically 100 times lower than uncoated PET. LCPs also provide a better moisture-barrier than experimental PET films having inorganic coatings. However, the LCP material by itself is very fragile and may be better suited for use in a laminate construction; it is also a relatively expensive material. Polyethylene naphthalate (PEN) has been identified as a high-performance material for the food packaging industry. Although it does have better moisture-barrier properties than PET, uncoated PEN is inadequate for PV applications. The water vapor transmittance rate (WVTR) of DuPont Teijin's experimental PEN / Al / PET laminate is below the detection limit of our Mocon unit, even at 85°C (see open circle in Fig. 3). If adhesion to EVA can be maintained during damp-heat exposure, this would be a very useful backsheet. The Isovolta Tedlar-SiO$_x$-PET backsheet exhibits barrier properties intermediate between uncoated PET and some experimental oxide/nitride-coated PET films. PNNL's multilayer-coated PET exhibits very low WVTR. However, it does not adhere to EVA during lamination.

Table 1. Preliminary test results for various backsheet materials.

Sample	Results
LCP	Excellent WVTR
NREL PECVD-coated PET	Passes initial tape peel test; fails tape peel test within 500 h. Poor WVTR properties (i.e., not much better than uncoated PET); excellent initial peel strength; total delamination of backsheet from EVA after 25 h exposure to damp-heat
Isovolta commercial products	Laminates with Al foil or an SiO$_x$ coating have maintained intermediate peel strength up to 2000 h damp-heat exposure; the Tedlar-PET-Tedlar construction degrades with exposure; Laminate with SiO$_x$ coating exhibits 4-6 X improvement in WVTR over uncoated PET
Experimental laminate from DuPont Teijin Films	Excellent WVTR results; backsheet progressively delaminates from EVA with damp-heat exposure (total delamination after 500 h)
PECVD-coated PET from AKT	2 of 10 samples continue to pass scotch tape peel test after 1850 h damp-heat exposure
PNNL multilayer-coated PET	Passes scotch tape peel test after 634 h damp-heat exposure; fails after 967 h; multilayer coating does not adhere to EVA; excellent WVTR

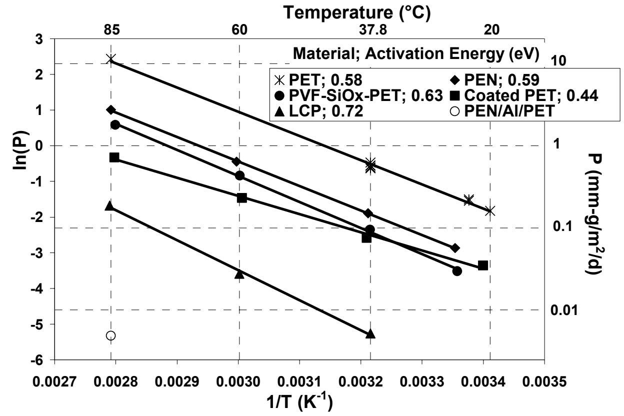

Fig. 3. Arrhenius plot of permeability for backsheets at 85% relative humidity (RH).

Combined Packaging

Several experiments were performed to quantify the relative effectiveness of various combined packaging strategies and components (i.e., backsheets, encapsulants, edge sealants) in preventing moisture-induced degradation of thin-film devices. The performance of small (laboratory-scale) PV devices is difficult to characterize without compromising the integrity of the protective package. However, exposure to damp-heat aggressively corrodes aluminum, which is often used in PV modules (e.g., as interconnects and back contacts). Consequently, thin-film aluminum coatings were vacuum deposited onto glass substrate test articles to simulate a PV device and provide a rapid visual indication of damage. The extent of degradation was documented with digital imagery as a function of time of exposure to damp-heat. Without any packaging, the unprotected aluminum corrodes vary rapidly (see Fig. 4). A number of backsheet / encapsulant combinations were laminated to the aluminized glass and were exposed to damp-heat for 700 h.

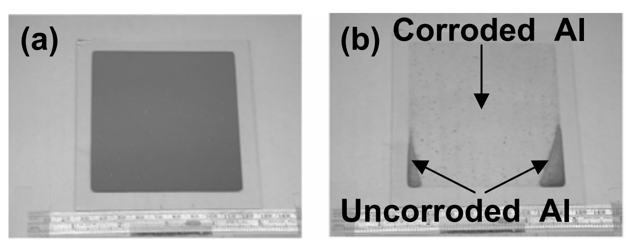

Fig. 4. Unprotected aluminized glass substrates (a) as deposited and (b) after 19 h exposure at 85°C/85% RH.

Samples with a breathable PET backsheet provided very good protection of the Al layer (see Fig. 5). Although moisture readily passes through the breathable PET backsheet, only slight corrosion is evident after damp-heat exposure. One possible explanation for this result is that the aluminum interface is passivated against corrosion by the EVA encapsulant. If this is true, then other constructions of EVA / Al-glass should not corrode.

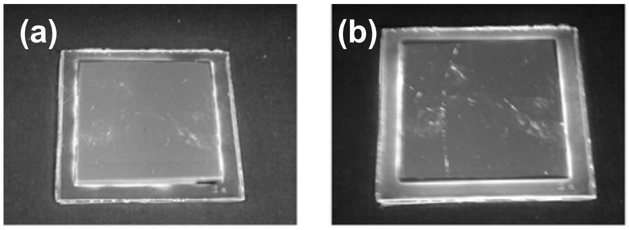

Fig. 5. PET / EVA / Aluminized glass (a) initial and (b) after 700 h exposure at 85°C/85% RH.

However, substantial bulk corrosion of Al occurred for Glass / EVA / Al-glass samples. Moisture ingress occurred from the edges on a time scale of about 250 h [1]. A “doughnut” configuration was used whereby the glass backsheet was laminated to the aluminized glass substrate using EVA along the edges and in the center such that there was a ring-shaped area in which there was no EVA in contact with the aluminum (see Fig. 6). After 700 h of damp-heat exposure, the aluminum in contact with EVA corroded, whereas the area of aluminum that was not in contact with EVA did not corrode. This suggests that EVA does not passivate aluminum, and that corrosion of the aluminum may be catalyzed by by-products (possibly acetic acid) within the encapsulant that cannot readily egress through the glass backsheet.

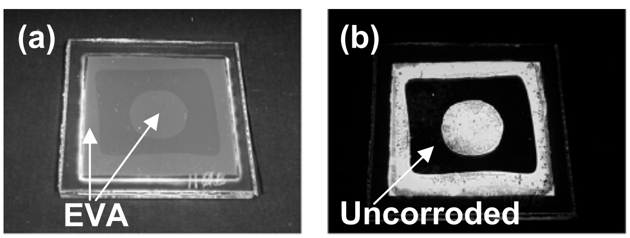

Fig. 6. Glass / EVA (partial) / Aluminized glass (a) initial and (b) after 700 h exposure at 85°C/85% RH.

Results for other package combinations include:

- Samples with the BRP-C encapsulant exhibited excellent protection of the aluminum layer, independent of the type of backsheet.
- Samples with the experimental DuPont Teijin backsheet did not exhibit aluminum corrosion, even though its adhesion to EVA was severely compromised by damp-heat exposure.
- Properly wetted edge seal materials demonstrated an outstanding ability to prevent moisture ingress in glass / glass constructions, even when a bead-blasted edge-delete existed.

CONCLUSIONS

Improved packaging materials are required to increase reliability of thin-film PV modules. We have evaluated a large number of backsheet and encapsulant materials in terms of their moisture-barrier properties and their ability to maintain good adhesion during damp-heat exposure. Several promising packaging candidates have been identified. We have also investigated the effectiveness of several combined packaging strategies and constructions to provide increased protection of PV modules. Glass / glass laminate constructions were often found to trap harmful compounds that catalyzed moisture-driven corrosion of aluminum. Constructions with breathable backsheets allow higher rates of moisture ingress, but also allow egress of deleterious substances, thereby reducing corrosion.

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